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TESTING AEROSPACE GEARS FOR BENDING FATIGUE, PITTING, AND SCUFFING

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ABSTRACT

This work was motivated by the goal to increase the power to weight ratio of rotorcraft drive systems. Experiments were conducted to establish the performance of gears made from an aerospace alloy used in production aircraft. Bending fatigue, pitting, and scuffing test procedures and results are documented. The data establishes a baseline for evaluation of new technologies. Recommendations are made to improve test procedures for future work.

INTRODUCTION

One of the goals for the U.S. Army's Future Advanced Rotorcraft Drive System Program is to demonstrate a 55% power to weight improvement for the drive system relative to that of a rotorcraft fielded in the year 2000. The gear steel used in the selected baseline fielded aircraft was evaluated using component level tests to establish performance for bending fatigue, pitting, and scuffing. The data from these experiments can be used to evaluate and validate new technologies such as new alloys and manufacturing processes.

TEST GEARS

Test gears were made from steel alloy meeting specification SAE AMS 6308D and additional company-specific proprietary material specifications. The material was produced by the VIM-VAR method and forged. Gears were case carburized and hardened to produce a case depth prior to grinding of 0.10-0.12 mm, case hardness of 81-83 HRA (61-63 HRC), and core hardness of 33-41 HRC. Flanks and roots were ground on a generating type gear grinder with maximum stock removal of 0.25 mm. Gears were shot peened after grinding followed by superfinishing, achieving an isotropic surface with a measured roughness less than 0.2 micrometer Ra.

The gear geometry for the pitting and bending fatigue tests were "NASA standard test gear" geometry, 3.175 mm module (8-pitch), 28 tooth gears with face width of 6.35 mm (see ref. 1 for more details of geometry). The gear geometry for the scuffing tests were 4.233 mm module (6-pitch), 21 tooth gears, 6.35 mm face width. The tip relief magnitudes were 0.051 mm (pitting) and 0.018 mm (scuffing). Circular lead crown magnitudes were 0.010 mm (pitting) and 0.015 mm (scuffing) at the extreme of the face width.

BENDING FATIGUE TESTS

Bending fatigue testing was done using the single tooth bending method. Testing was conducted using a standard fatigue test system and fixture to hold and orient the gear with the base circle tangent to the applied load. The fixture and mounting was rigid and carefully aligned to the fatigue test frame. Tests were conducted using unidirectional loading, sinusoid waveform, R ratio of 0.02, and load control at 20 Hz. The gear angular rotation was set using a dedicated gage block to load the tooth at the high point of single tooth contact (if mated as a 1:1 ratio pair). The loading rod stroke was monitored, and fatigue failure was declared when the loading rod stroke increased by 2% relative to that for the new gear tooth. At this point a crack had initiated and propagated with size in the order of the case depth. Some tests were suspended with no failure (runouts) after 12 million load cycles. Stress produced by load was determined using a 3-dimensional finite-element method. The analysis model geometry was adjusted to match the test gear tooth thickness and root-fillet geometry shape as measured by a digital microscope. For a 1 N load, the maximum principal tensile stresses are 143 kPa and 111 kPa at positions of the center and edge of the face width, respectively. Results of 19 single tooth bending fatigue tests are listed in Table 1.

Table 1 - Bending Fatigue Test Results

Load (kN)	Load Cycles (millions)	Result	Load (kN)	Load Cycles (millions)	Result
13.8	12.0	5 runouts	15.3	0.062	fatigue
14.5	12.0	2 runouts	15.3	2.81	fatigue
14.9	1.82	fatigue	15.3	4.15	fatigue
14.9	12.3	fatigue	15.3	6.95	fatigue
14.9	12.0	runout	15.3	12.0	runout
			15.3	12.0	2 runouts
			17.1	0.032	fatigue
			17.1	0.239	fatigue

PITTING TESTS

Pitting tests were conducted using a power-recirculating rig with test gears operating at 10,000 rpm. Tests were conducted at constant, feedback-controlled torque measured by a strain-based torque meter. Two lubricants were used, one a 5 cSt oil meeting the DOD-PRF-85734 specification and the second a 9 cSt research oil having a proprietary nanotechnology additive. Oils were filtered by a 3-micron rated filter. Lubrication of the test gears was by two radially-directed lube jets with supply pressure of 800 kPa and temperature of 65 deg. C. Tests were conducted continuously until pitting occurred as detected by a rise in the measured vibration. Tests completing 300 million cycles with no failure were suspended (runouts).

Preliminary tests were conducted at 185 Nm torque with all tests resulting in runouts. Increasing the torque to 230 Nm produced excessive hard-lines that were dominating the test results, as tip relief and tip edge break were insufficient for such torque. The test gears were processed by a spindle deburr operation to remove some material from the tooth tips followed by superfinishing. This approach allowed the gears to operate at 230 Nm without excessive hard-line of contact at the tooth tips. Based on a load distribution program analysis (Ref. 2), the maximum contact pressure for 230 Nm of torque was 2.4 GPa. For future work, it is recommended to carefully choose a tip relief modification and magnitude, mindful of the torque needed to achieve such contact pressure. A total of 21 tests were completed with 11 resulting in pitting and 10 resulting in runouts at 300 million cycles. For purposes of Weibull analysis of the data by regression of median ranks, the data for both oils were combined into one dataset. This was done with the concept that all tests were operating with full elastohydrodynamic film condition, and so the influence of viscosity on pitting life should not be strong (Ref. 3). For such combined dataset, the Weibull slope was determined as 1.1, Weibull scale as 310 million cycles, and L_{10} life as 42 million cycles.

SCUFFING TESTS

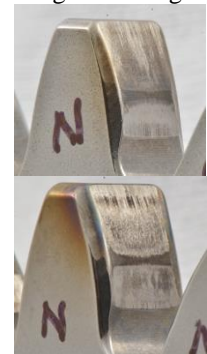
Scuffing tests were conducted using the same power recirculating rigs as was used for pitting tests, but with some

operational differences. A single lube jet was directed radially at the pinion near the into-mesh region. The temperature of the oil in the supply line to the jet was 140 deg. C. Tests reported herein used a 5 cSt oil meeting DOD-PRF-85734. Oil was drained and replaced after every 3 scuffing tests. The gears were first operated for 30 minutes at low torque and speed to allow the additives to take effect on the tooth surfaces. Test gear speed for scuffing tests was 8,400 rpm rather than the maximum rig speed of 10,000 rpm. The lower speed was used to avoid excessive dynamic torques, as the meshing frequency of the 21-tooth test gears excited a strong mode in the vicinity of the maximum rig speed. A load-stage test approach was used, with each load stage duration of 75,000 cycles. The rig was stopped at completion of each load stage for visual assessment, aided by magnification, to check for scuffing of each test tooth. Thermocouples to measure the oil-air mixture in the vicinity of the test gear periphery, located near out of mesh positions, were monitored, and monitoring such data sometimes allowed for detection of scuffing in real time. Experience showed the importance of managing the rig speed-up and slow-down. This was done by applying a small torque to avoid even a short duration operation at a combined low speed and high torque condition and to avoid dwelling at speeds exciting rig vibration modes. The first three load stages were torques of 55, 85, and 115 Nm. Subsequent load stage increments were additional 10 Nm torque for each stage. Seven such scuffing tests were completed. Table 2 summarizes the results. If scuffing was found on a pinion tooth, the mating tooth on the gear was also scuffed. In some cases, heat from the scuffing event was sufficient to discolor the steel, but not in all cases. Figure 1 shows typical appearance of scuffing on a pair of mating teeth.

Table 2 – Results of Load-Stage Scuffing Tests

Test #	Scuffing Torque (Nm)	Number of tooth pairs scuffed
1	145	14
2	55	5
3	175	1
4	165	12
5	155	2
6	145	4
7	155	8

Figure 1 – Typical Appearance of Scuffing on Mating Teeth



REFERENCES

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